Planetary Drilling and Resources at the Moon and Mars

Pioneer Natural Resources

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Abstract

Planetary Drilling and Resources at the Moon and Mars

Drilling on the Moon and Mars is an important capability for both scientific and resource exploration. The unique requirements of spaceflight and planetary environments drive drills to different design approaches than established terrestrial technologies. A partnership between NASA and Baker Hughes Inc. developed a novel approach for a dry rotary coring wireline drill capable of acquiring continuous core samples at multi-meter depths for low power and mass. The 8.5 kg Bottom Hole Assembly operated at 100 We and without need for traditional drilling mud or pipe. The technology was field tested in the Canadian Arctic in sandstone, ice and frozen gumbo.

Planetary resources could play an important role in future space exploration. Lunar regolith contains oxygen and metals, and water ice has recently been confirmed in a shadowed crater at the Moon's south pole. Mars possesses a CO_2 atmosphere, frozen water ice at the poles, and indications of subsurface aquifers. Such resources could provide water, oxygen and propellants that could greatly simplify the cost and complexity of exploration and survival.

Bio

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Jeff George is a project manager, systems engineer, technologist, and advanced mission planner at the NASA Johnson Space Center in Houston, TX. His responsibilities include developing mission architectures for human exploration of the Moon and Mars; leading the NASA/JSC Nuclear Systems Team to plan, assess and develop space nuclear power and propulsion technologies; and serving as Mission Architect for the planned RESOLVE lunar resource mission. Jeff led the successful collaboration of NASA and Baker Hughes Inc. to develop a low mass and power drilling technology through two prototype cycles and field testing in the Canadian High Arctic. Jeff earned his B.S. and M.S. in Nuclear Engineering from Texas A&M University.

Contents

30-45 min

40 charts

Why Drill ?

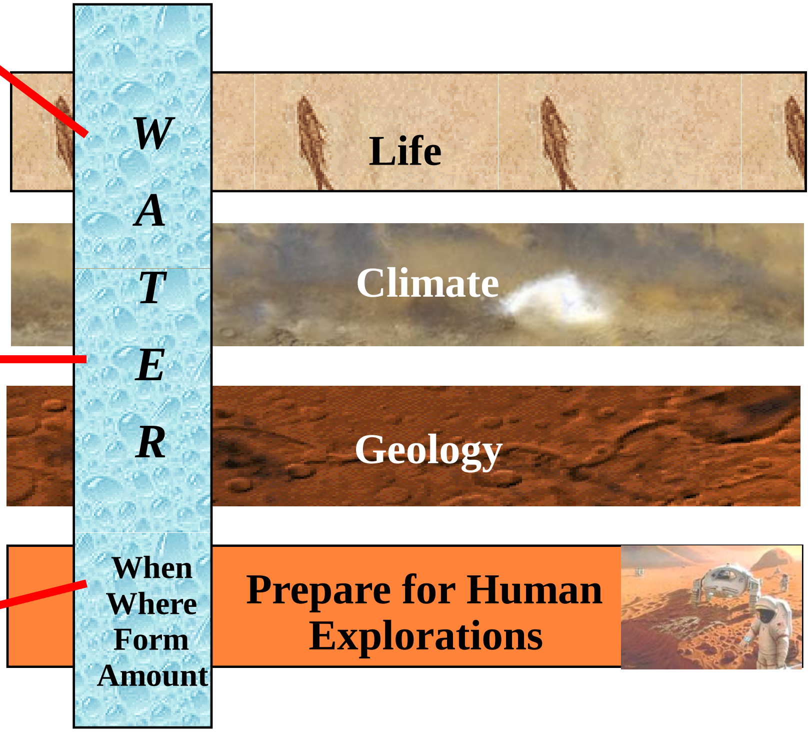
Mars "Follow the Water" Strategy

Subsurface liquid water best chance of finding Martian life

Cycling between subsurface and atmosphere, sedimentary record

Water is critical resource for HEDS and permanent Mars presence

Common Thread



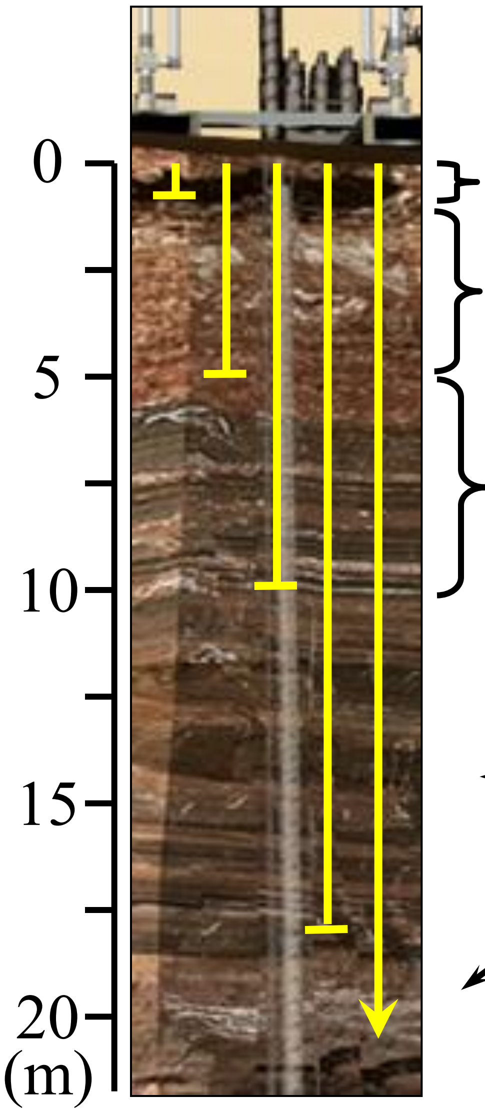
Understand the Potential for Life Elsewhere in the Universe

Understand the Relationship to Earth's Climate Change Processes

Understand the Solid Planet: How It Evolved

Develop the Knowledge & Technology Necessary for Eventual Human Exploration

Mars Subsurface Scientific Objectives



100’s–1000’s m?

Surficial processes: min., petrology, physical props. (density, perm.), weathering/erosion processes, impact gardening, gradient in surficial oxidant, EM

Pre-weathering processes
- sedimentation processes, stratigraphy
- past environments, history of volatiles
- Geophysics: Heat flow, thermal state, seismic

- Organic geochem below oxidized zone
- presence of ice?

- Bedrock: Rock-forming processes, history

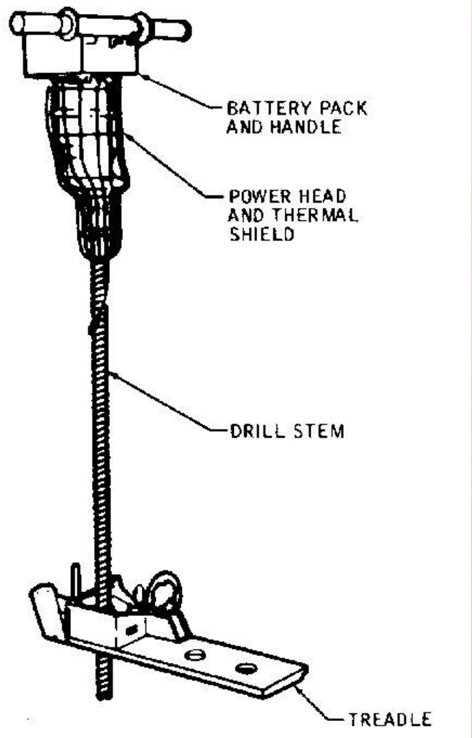
- Sample permafrost or massive, segregated ground ice, volatile hydrates

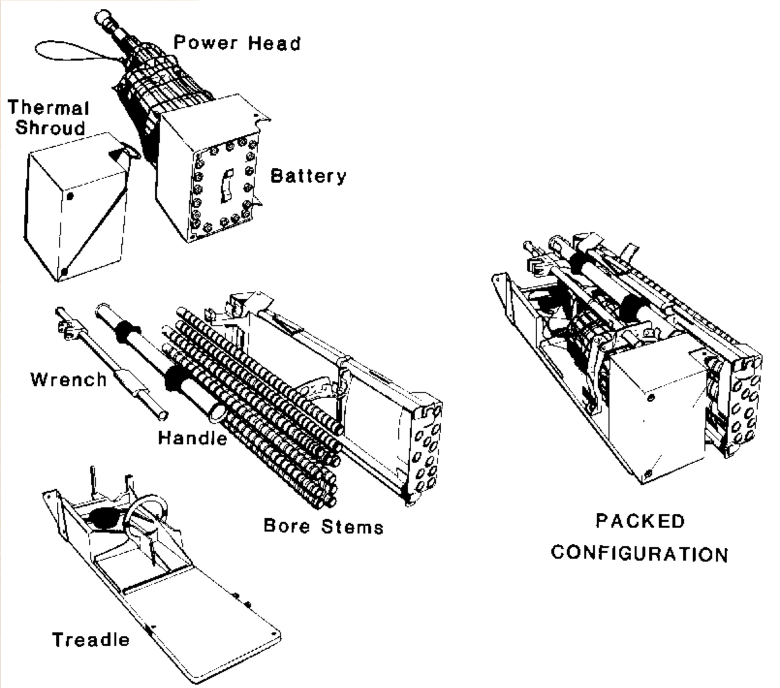
- Access Liquid Acquifers?

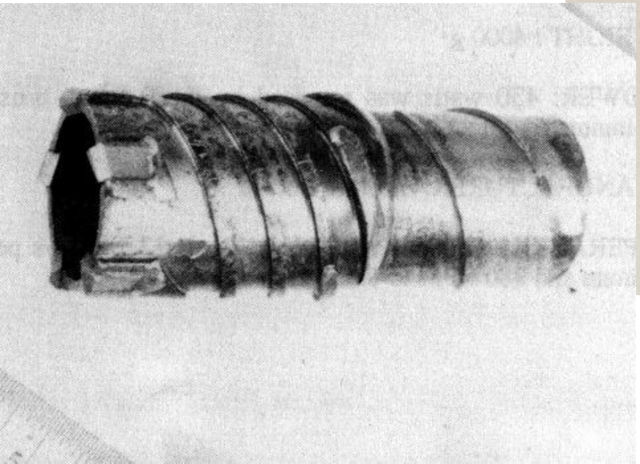
Apollo Lunar Surface Drill (ALSD)

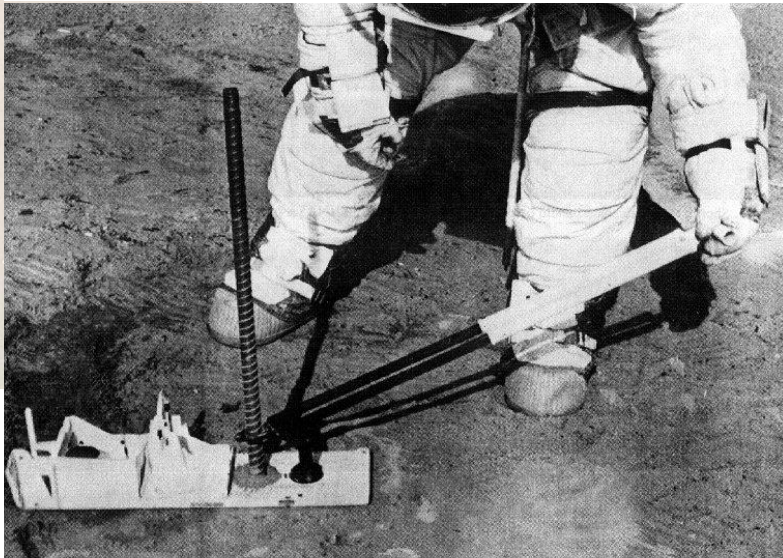
- **First "Cordless" Drill (?)**
- **Martin-Marietta, Black&Decker**
- **Handheld drive unit**
  - Battery powered
  - ~430 - 500 W
- **Rotary-percussion action**
  - 280 rpm
  - 2270 bpm
  - 40 in-lb / blow
- **Coring Bit:**
  - 6 cm long x 2 cm ID
  - Steel body + 5 brazed tungsten carbide tips
- **Drill stem:**
  - 40cm long, 2.5cm OD, 2.0cm ID
  - Titanium alloy
  - External auger flights
- **Carrier & Treadle/removal tool**
- **Total depth capability = 3.0 m**
- **Total system mass = 13.4 kg**

ALSD Elements



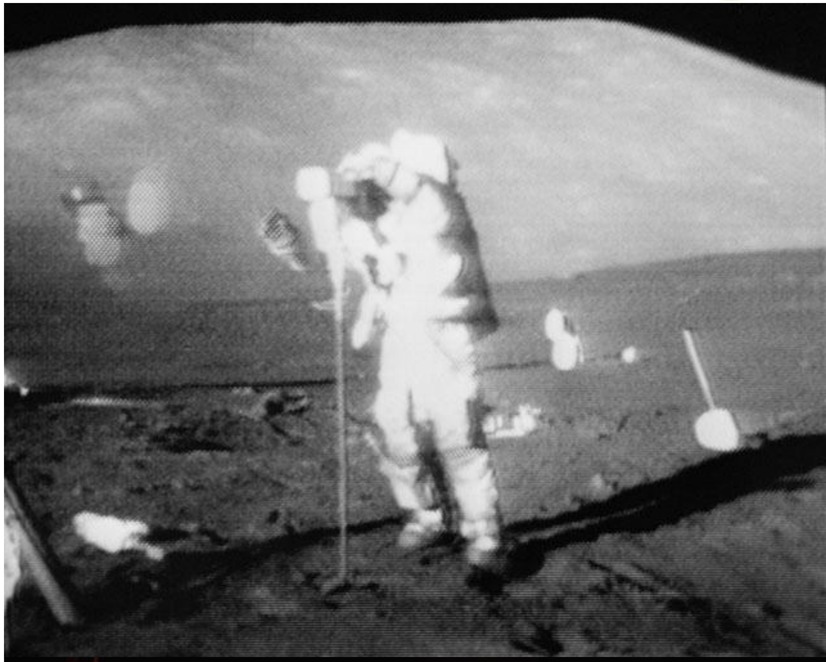


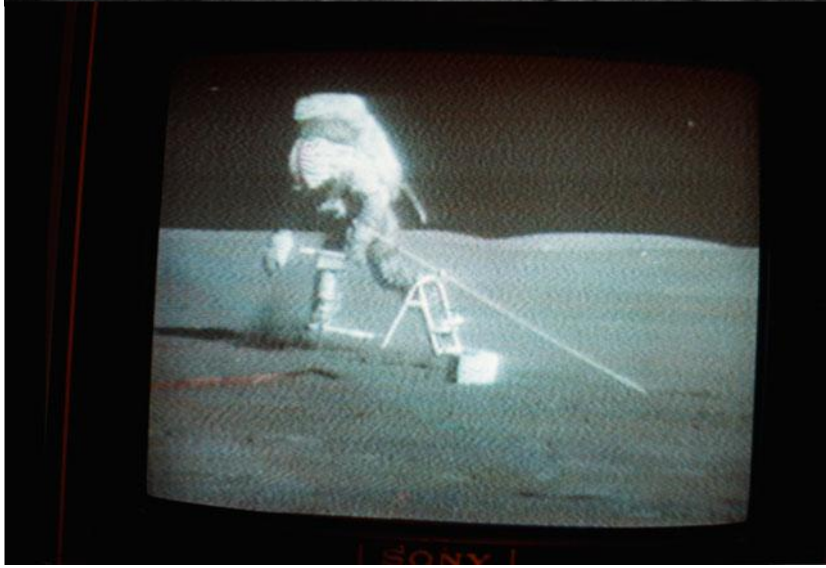




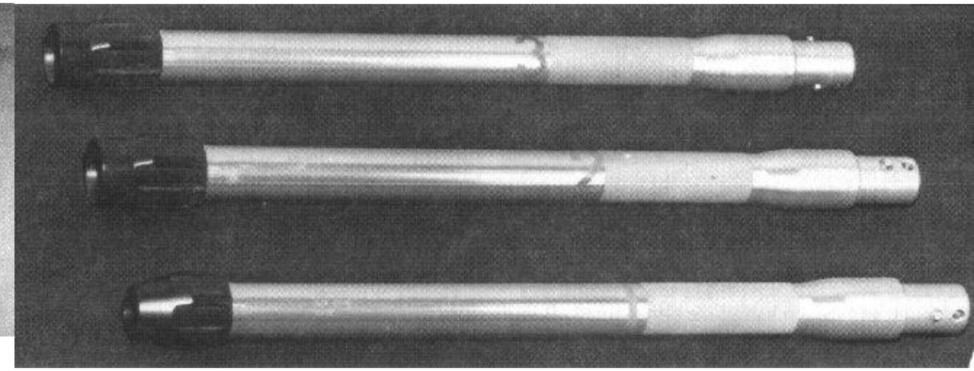
Apollo Lunar Drilling Results

- Flew on Apollo 15, 16, 17
- Purpose:
  - Acquire core samples
  - Emplace heat flow thermocouples
  - Neutron probe
- ~5-15 minutes to drill each hole
- Astronauts learned to:
  - “Hold-back” as drill advanced
  - Clear cuttings to surface before remove
- A-15 drill stem very difficult to remove
  - Both astronauts & sprained shoulder
- Redesign & “treadle/jack” aided 16, 17
- 7.6 m cum. Exc. recovery & stratigraphy
- Regolith: jagged, interlocked agglutinates
- Top few cm’s: “fluffy” unconsolididated
- Deeper cm’s: closely packed, 1.6-2.1 g/cc.
- Hope: Cores would reflect slow evolution history of surface
- Cores surprisingly homogenous- no distinct ancient surfaces found
- Deepest core last exposed ~1B yr ago





Other Apollo Sampling Tools



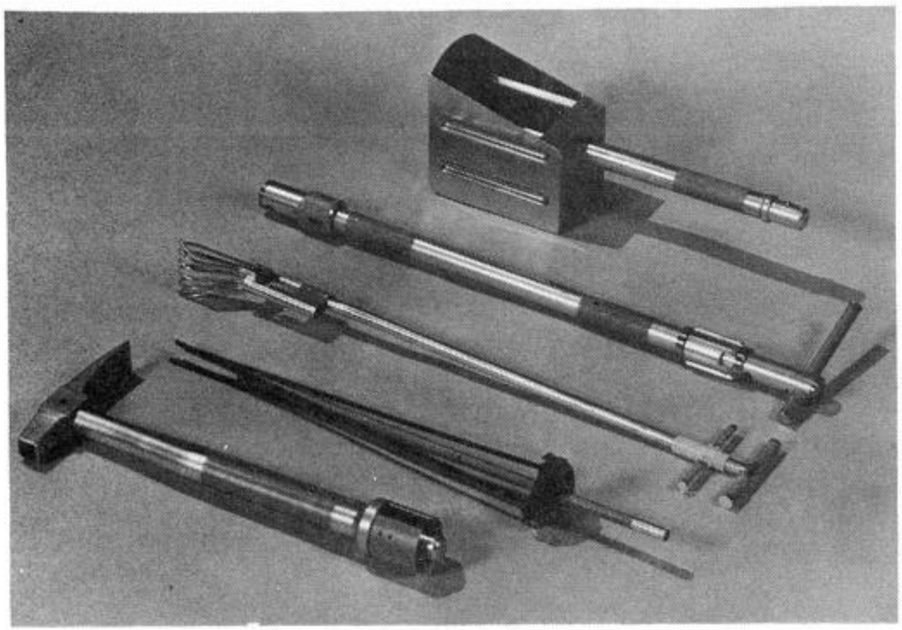
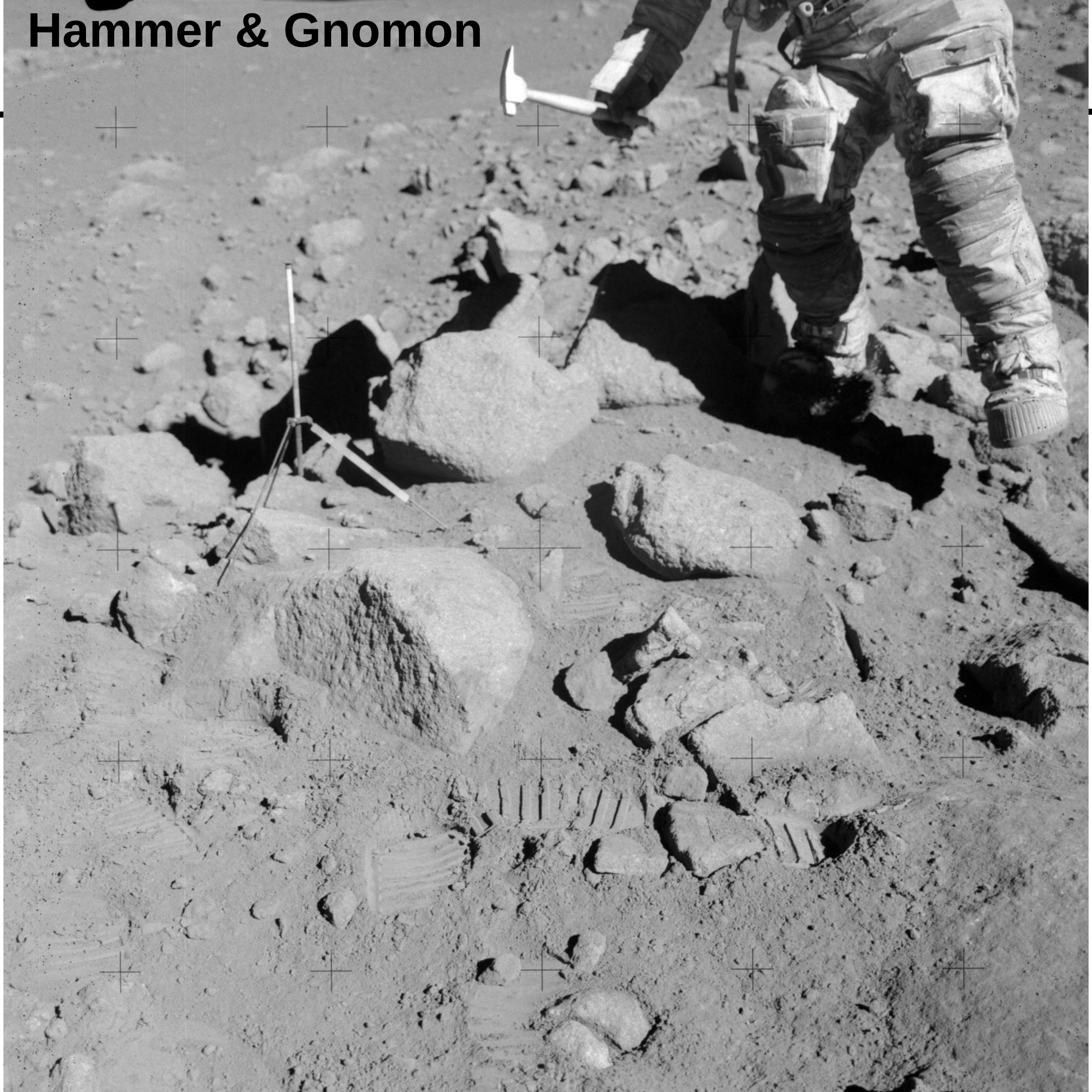


Fig. 26. Tools of the type used on Apollo 11 (L to R): lighter weight hammer, gnomon, shorter tongs, shorter extension handle, box-shaped scoop. The extension handle was used with the hammer and the scoop (NASA photo S69-31860).

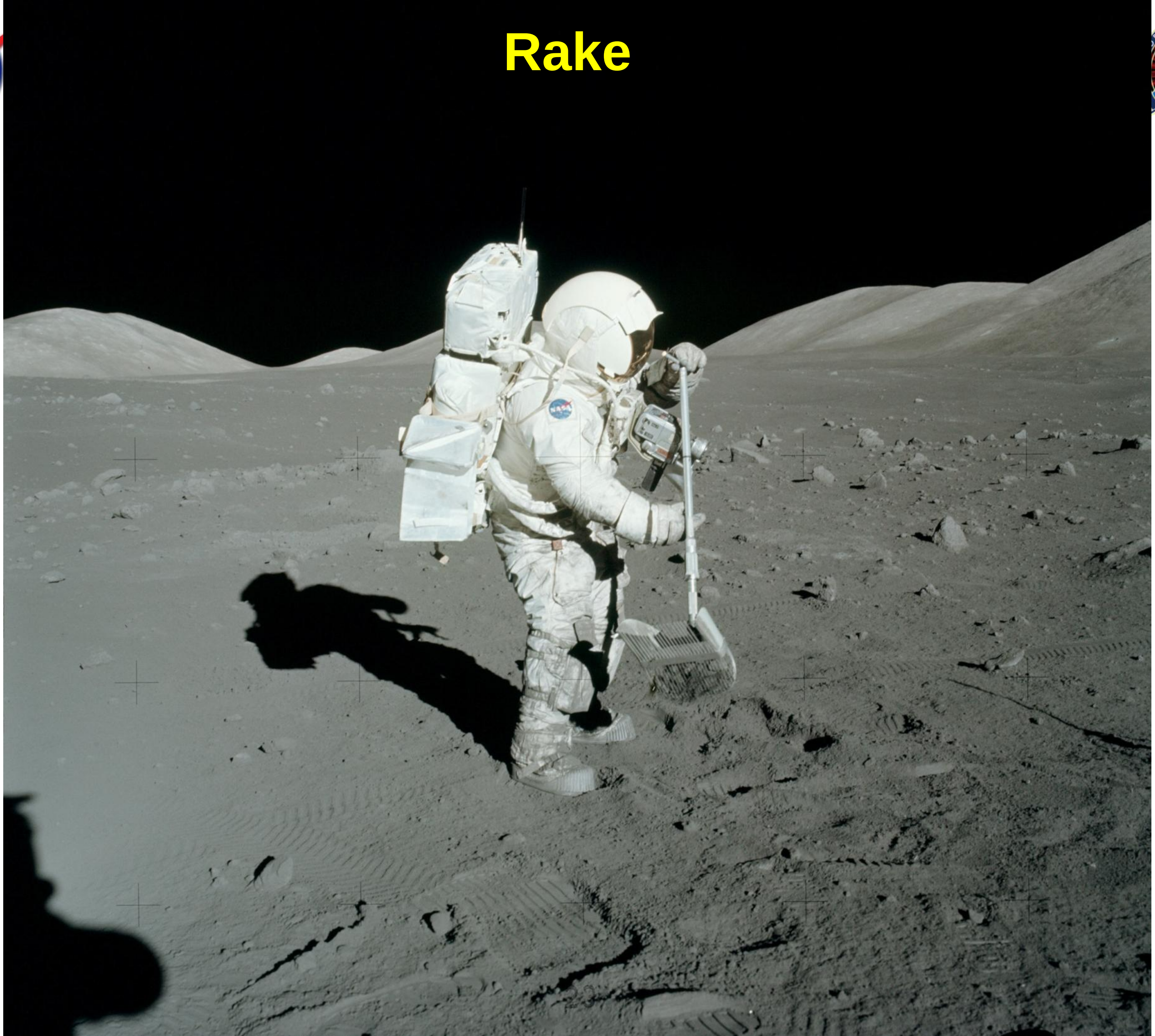
Fig. 72. Apollo 16 Lunar Sample Return Container upon opening in the Lunar Receiving Laboratory. The box contains a large rock, several documented sample bags with the fold-over aluminum tabs, and a 4-cm diameter drive tube (NASA photo S72-36984).

Tongs & Rake

Hammer & Gnomon



Rake



Drill Project Goals & Objectives

***Vision* (why):** Explore Mars' subsurface, to understand history, climate, life, and resources.

***Mission Statement* (what):** Develop a deep drilling and sample acquisition capability.

Project Major Goals:

Goal I:
Advance Drill to TRL=4
(System in lab environment)

Goal II:
Advance Drill to TRL=5
(System in field environment)

Goal III:
Participate in M/ADD Project and demonstrate in Arctic

Goal IV:
Demonstrate Rover-deployed drilling

"Mark I" Mars Drill Project Objectives & Requirements

"Mark II" Mars Drill Project Objectives & Requirements

NASA / Baker Hughes Inc. Mars Drill

Space Act Collaboration

- ***NASA / Johnson Space Center / EX***
  - Project Management
  - System Design, Integration, and Test
  - BHA Assy (Anchor, Force-on-Bit, Drive Motor)
  - Surface Support Assembly
  - Control Electronics (Hardware)
- ***Baker Hughes Incorporated***
  - Industry Partner
  - Drilling Mechanics
  - Ops. Expertise
  - BHA Auger, Bit, Core Break/Trap S/A's

- NASA/JSC / SCOUT Rover
  - Mobility; Rover/Drill Demo
- NASA/JSC / EC Rover
  - Mobility; Rover/Drill Demo
- NASA/JSC/ EX ACES Van
  - Remote Operations Demo
- NASA/JSC / ARES
  - Moon Science Objectives
  - Moon Subsurface Environment
- NASA / Ames Research Center
  - PI for Code S/ASTID "M/ADD" Project
  - Automation

- Lunar and Planetary Institute
  - Mars Science Objectives
  - Mars Subsurface Environment
- UC Berkeley
  - Fundamental Research
  - Component Laboratory Testing
  - Modeling and Simulation
- University of Texas
  - Leadership & Outreach
- MacGill University; University of Toronto
  - Arctic Multidisciplinary Science
  - Sample Contamination

Design Approach

Challenges of Drilling on Mars:

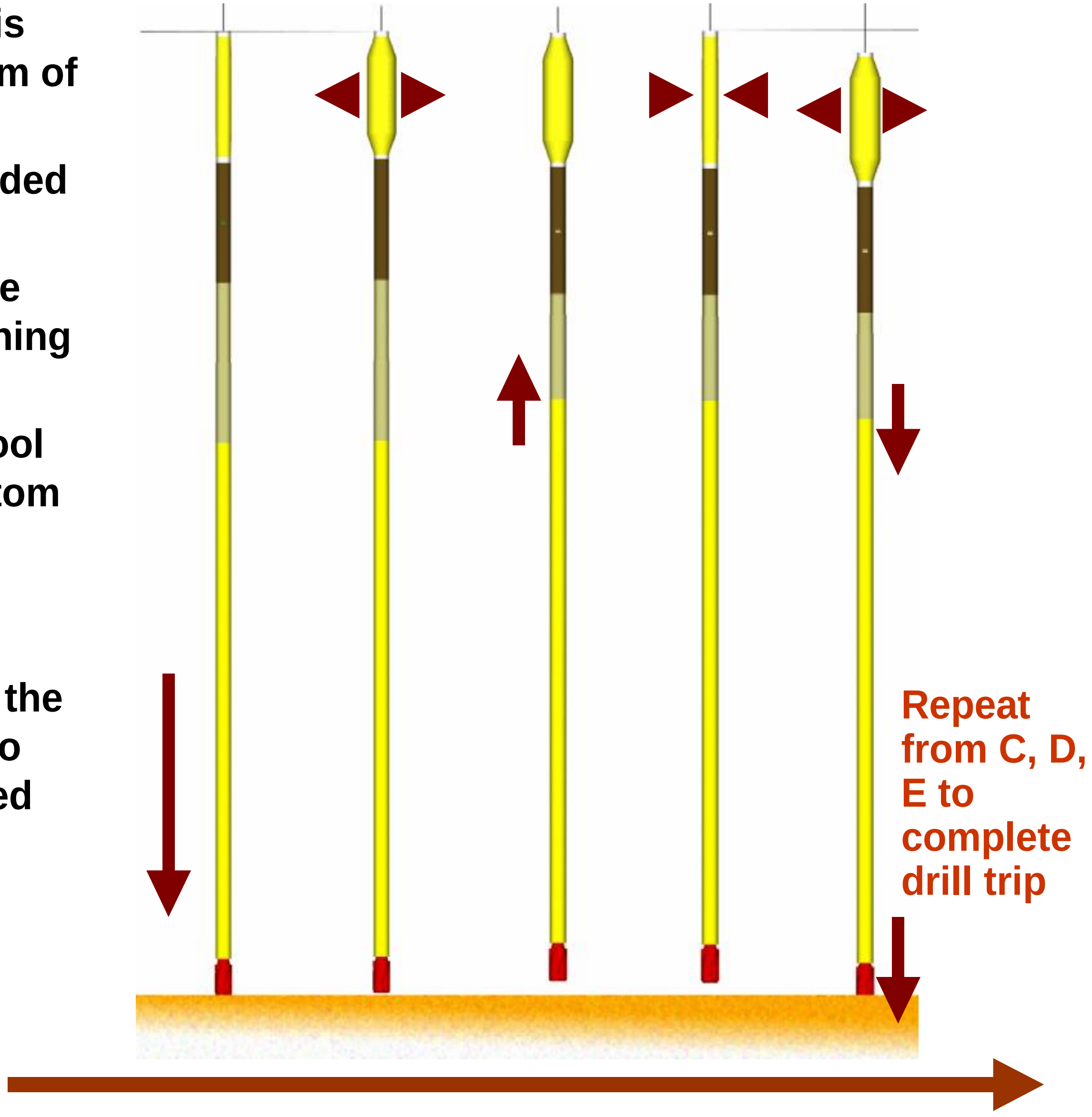
- Achieving Depth
- Limited Mass
- Limited Power
- Aseptic Sampling
- No Drilling Fluids:
  - Cuttings Removal
  - Heat Transport
  - Sample Contamination

Our Approach:

Drilling Function	Technical Approach	Features
• Sample acquisition	• Dry	• Continuous Core & Cuttings Record
• Comminution	• Rotary Coring Bit	• Low Sample Contamination
• Cuttings Removal	• Downhole Motor	• Low Mass
• Torque	• Wireline	• Low Power
• Force-on-bit	• Bailing	• Deep capable
• Power Transmission	• Borewall Anchoring	• Modest Penetration Rates
• Cooling	• Internally applied Force-on-bit	• Sensitive to Formation Stability

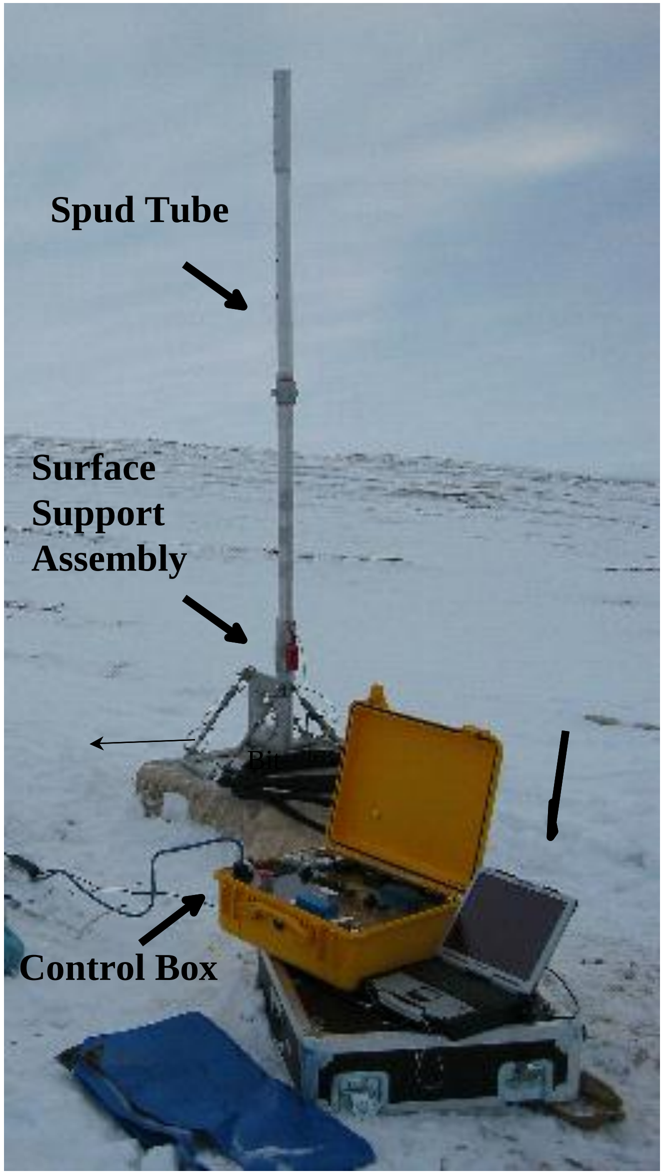
Coring / Bailing Operational Sequence

- **A – Initial Deployment, Tool is Lowered to tag the Bottom of the Drill Hole**
- **B - Anchor Module is Expanded against bore**
- **C – The winch pulls up on the wireline, setting and latching the FOB spring**
- **D – Anchor is Contracted; Tool is lowered to tag the Bottom of the drill hole to initiate drill bite.**
- **E – The Anchor is expanded, drill motor is started and the FOB Spring is released so that drilling force is placed on the rotating drill bit.**



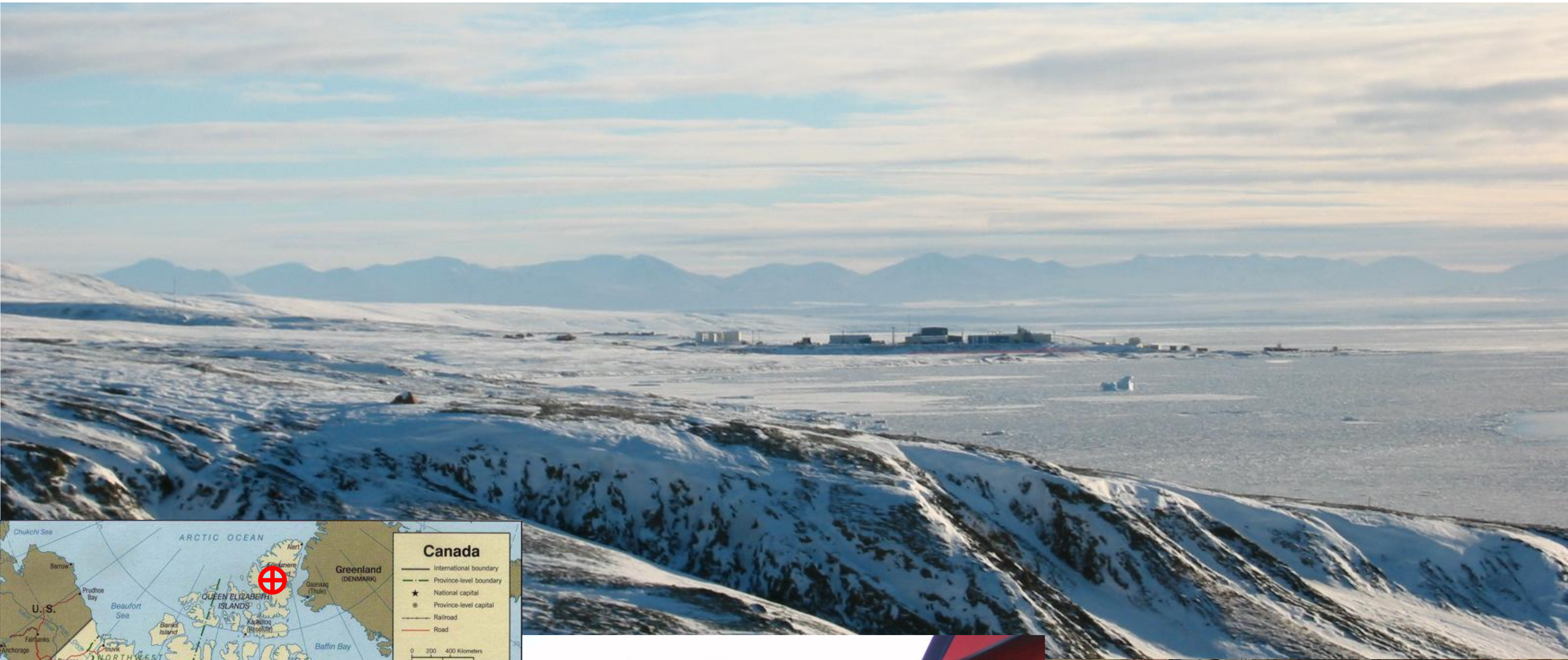
Mk2 Drill Elements & Characteristics

- **Bottom Hole Assy (BHA):**
  - **General**
    - Length: Approx. 7 feet
    - Diameter: approx. 1.75 inches
    - Weight: ~30 lbs
  - **Electrical**
    - Continuous Power: 100 W
    - Peak Power: 200W
    - Max. Voltage sent to BHA: ~30VDC
  - **Mechanical**
    - Max. Force-on-Bit: -200 to +200
    - Internal Stroke of AFOB Spring: ~0.25 inch
    - Drill Bit/Auger RPM: 0-225
- **Umbilical / Tether** (Power, Data, Recovery)
- **BHA Control Box (yellow box)**
  - Input Power: 120 VAC @ (.8 amps nominal)
  - Weight: 35 lbs
- **Surface Equipment (weight)**
  - Rock Support Fixture: ~25 lbs
  - Spud Tube: ~10 lbs
- **Laptop: Panasonic Toughbook**
- **Software: Labview** (Logging & Control)



Eureka Weather Station

Ellesmere Island, Canadian High Arctic

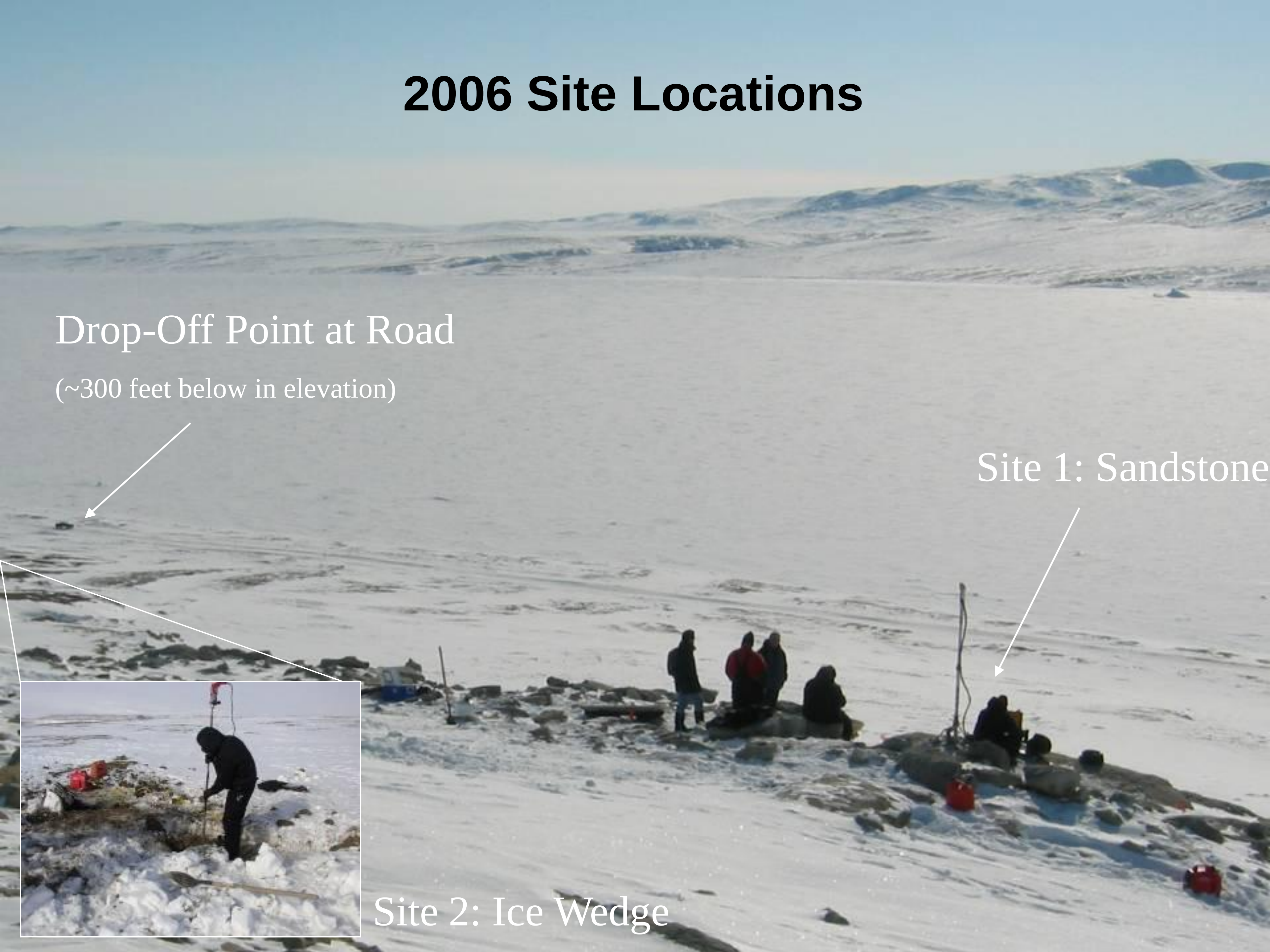


2006 Field Testing

Eureka, Ellesmere Island, Canada.

Field Test - Specific Ops

Ellesmere Island, Canadian High Arctic


2006 Site Locations
Drop-Off Point at Road
(~300 feet below in elevation)
Site 1: Sandstone
Site 2: Ice Wedge

2006 2m Sandstone

2004 Ice Drilling – 2 meters

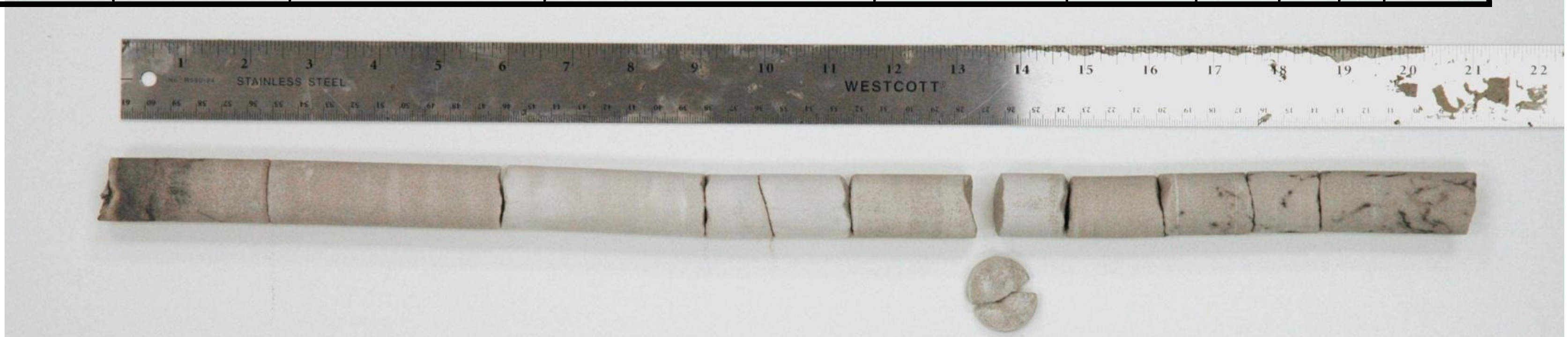
Critters

2004 Chris-Rock Cores & Bites

- **Second Sandstone Bore, Eureka, Sept. 2004**
  - **Bore Depth = 21.2” (0.5 m)**
  - **Total Core lengths = 21” (0.5 m)**

New Bit, Reaming

	Sunday				*Tuesday*				
Bite #:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Length:	**2.8”**	**4.0”**	**5.0”**	**3.8”**	**1.5**	**1.0**	**1.0**	**0.5**	**2.0”**
ROP:	**3.4”/hr**	**5.5**	**5.6**	**4.2**	**2.5**	**1.9**	**2.0**	**1.4**	**2.7”**



Core #:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Length:	**2.6”**	**3.5”**	**5.4”**	**3.1”**	**1.4**	**1.2**	**1.1**	**2.3”**

Field Performance: 2004 vs 2006

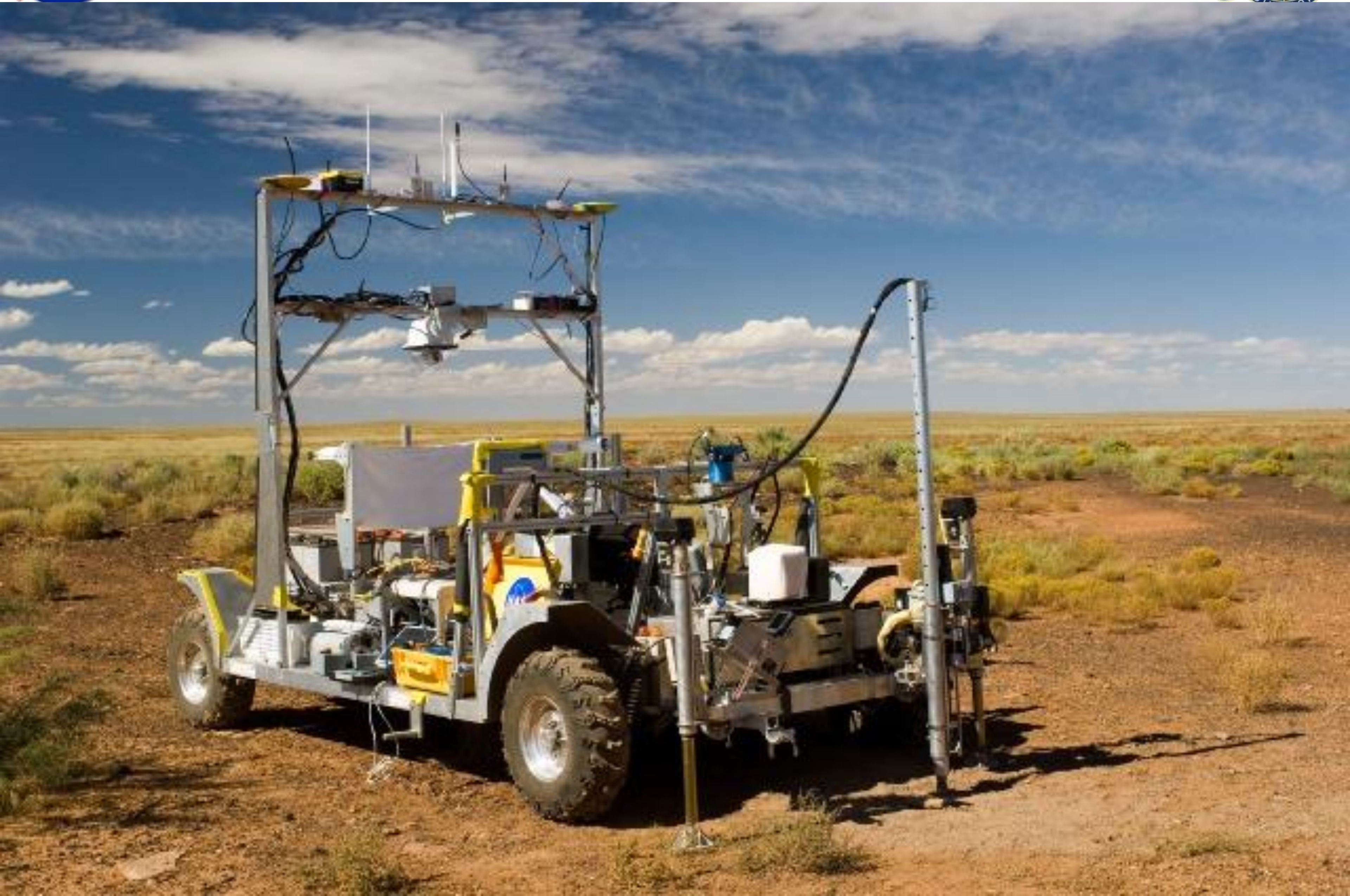
PERFORMANCE:	2004	2006
Max. Depth in Sandstone	0.5 meter	2 meters
Cum. Depth in Sandstone	1.1 meters	2 meters
Depth in Ice	2 meters in iceberg (1)	1 meter in ice wedge (2)
Average Drilling Rate	3.6 in/hr	8.1 in/hr
Average Drilling Power	60-120 Watts electric	60-175 Watts electric
Time on Bottom	724 min.	573 min.
Total Number of SS cores	16 cores	24 cores
Total Number of Drill days	5	5

(1) With MK IIa drill motor (manual force-on-bit))

(2) With MK IIb auger/drill bit (manual force-on-bit)

JSC / Baker Hughes Drill

Field Ops w/ Scout Rover, Meteor Crater AZ, Sept. 2005



Rover/Drill System Key Elements

- Scout Rover
- Mk2b Drill (BHA)
- Rover Support Assy
  - Spud Tube
  - Linear Actuator
  - Pitch, Roll Actuators
  - Inclinometer
  - Stabilization Jacks
  - Custom Bumper
- Infrared Camera
- Visual Camera
- Also (not shown):
  - Drill Control
  - RSA Control
  - Laptop & Labview S/W
  - Operators

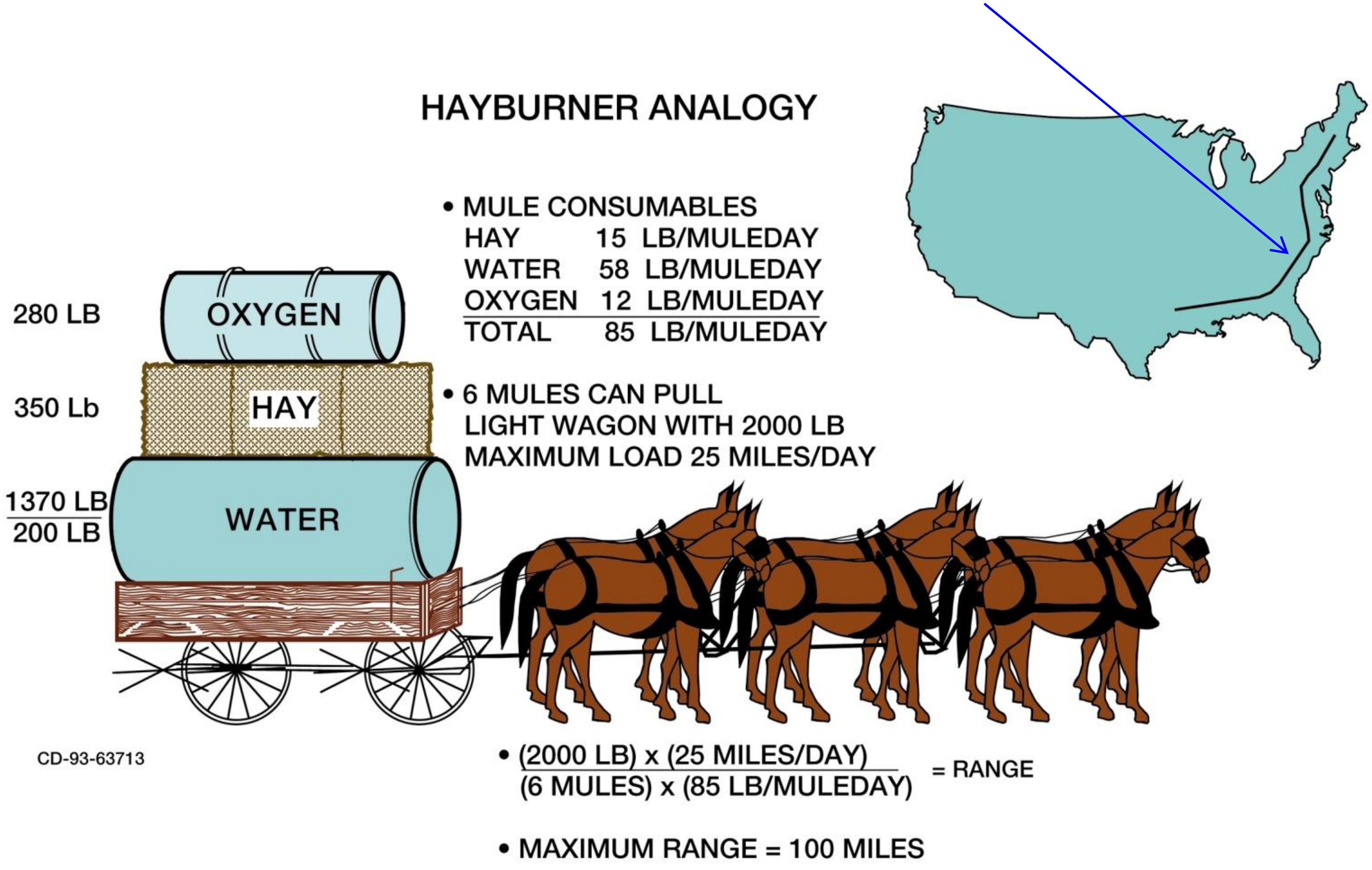
JSC/BHI Mars Drill Accomplishments

- ***<u>Successfully Achieved Major Project Goals:</u>***
  - **Mk1 Prototype Development, Lab Testing, and “TRL-4” Demo**
  - **Mk2 Prototype Development, Field Testing and “TRL-5” Demo**
  - **Arctic Field Testing and M/ADD Collaboration**
  - **Mobile Rover-deployed Drilling and Remote Command/Control**

- ***<u>Developed/Demonstrated Novel Approach for Planetary Drilling:</u>***
  - **Dry, rotary, coring, wireline, bailing Bottom Hole Assembly**
  - **Low Mass: 8.5 kg BHA**
  - **Low Power: 100 watts-electric operation**
  - **Depth: Multiple meters, extensible to 10’s+ meters**
  - **Asceptic core samples: 2.5 cm dia by 15 cm, continuous record**
  - **Modest Force-on-Bit: 387 N (87 lbf)**
  - **Rotary Speeds: 100-120 rpm**
  - **Modest Rate-of-Penetration: 20 cm/hr rate of penetration**
  - **2 m depths demo’d in Sandstone, Ice, Unconsolidated Sand**
  - **Five different Drill Bit technologies explored; Multiple Auger families**
  - **Applicable to Mars or Moon, and Robotic or Human Missions**

Settling the West

We wouldn't have gotten far if we couldn't use the local resources



Space Resources

Four major resources on the Moon:

- **Regolith**: oxides and metals
  - Ilmenite 15%
  - Pyroxene 50%
  - Olivine 15%
  - Anorthite 20%
- Solar wind volatiles in regolith
  - Hydrogen 50 – 150 ppm
  - Helium 3 – 50 ppm
  - Carbon 100 – 150 ppm
- **Water/ice** and other volatiles in polar shadowed craters
  - 1-10% (LCROSS)
  - Thick ice (SAR)
- Discarded materials: Lander and crew trash and residuals

Water is the Key Resources

- **Life Support**
- **Rocket Propellant**
- **Radiation Shielding**

Three major resources on Mars:

- **Atmosphere**:
  - 95.5% Carbon dioxide,
  - 2.7% Nitrogen,
  - 1.6% Argon
- **Water in soil**: concentration dependant on location
  - 2% to dirty ice at poles
- Oxides and metals in the soil

~85% of Meteorites are Chondrites

Ordinary Chondrites 87%

FeO:Si = 0.1 to 0.5

Fe:Si = 0.5 to 0.8

Pyroxene
Olivine
Plagioclase
Diopside
Metallic Fe-Ni alloy
Trioilite - FeS

Source metals (Carbonyl)

Carbonaceous Chondrites 8%

Highly oxidized w/ little or no free metal

Abundant volatiles: up to 20% bound water and 6% organic material

Source of water/volatiles

Enstatite Chondrites 5%

Highly reduced; silicates contain almost no FeO

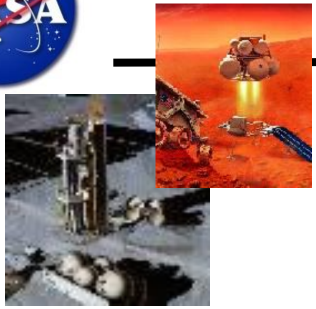
60 to 80% silicates; Enstatite & Na-rich plagioclase

20 to 25% Fe-Ni

Cr, Mn, and Ti are found as minor constituents

Easy source of oxygen (Carbothermal)

Space Resource Utilization Changes How We Can Explore Space



Space Resource Utilization

Mass Reduction

- >7.5 kg mass savings in Low Earth Orbit for every 1 kg produced on the Moon
- Chemical propellant is the largest fraction of spacecraft mass

Cost Reduction

- Allows reuse of transportation systems
- Reduces number and size of Earth launch vehicles

Risk Reduction & Flexibility

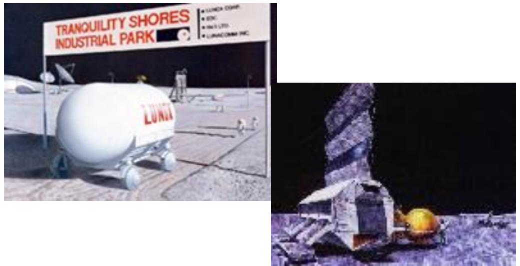
- Provides ‘safe haven’ capabilities for aborts and delayed cargo resupply
- Radiation and landing/ascent plume shielding
- Increases flexibility and options for contingency and failure recovery operations
- Reduces dependence on Earth

Expands Human Presence

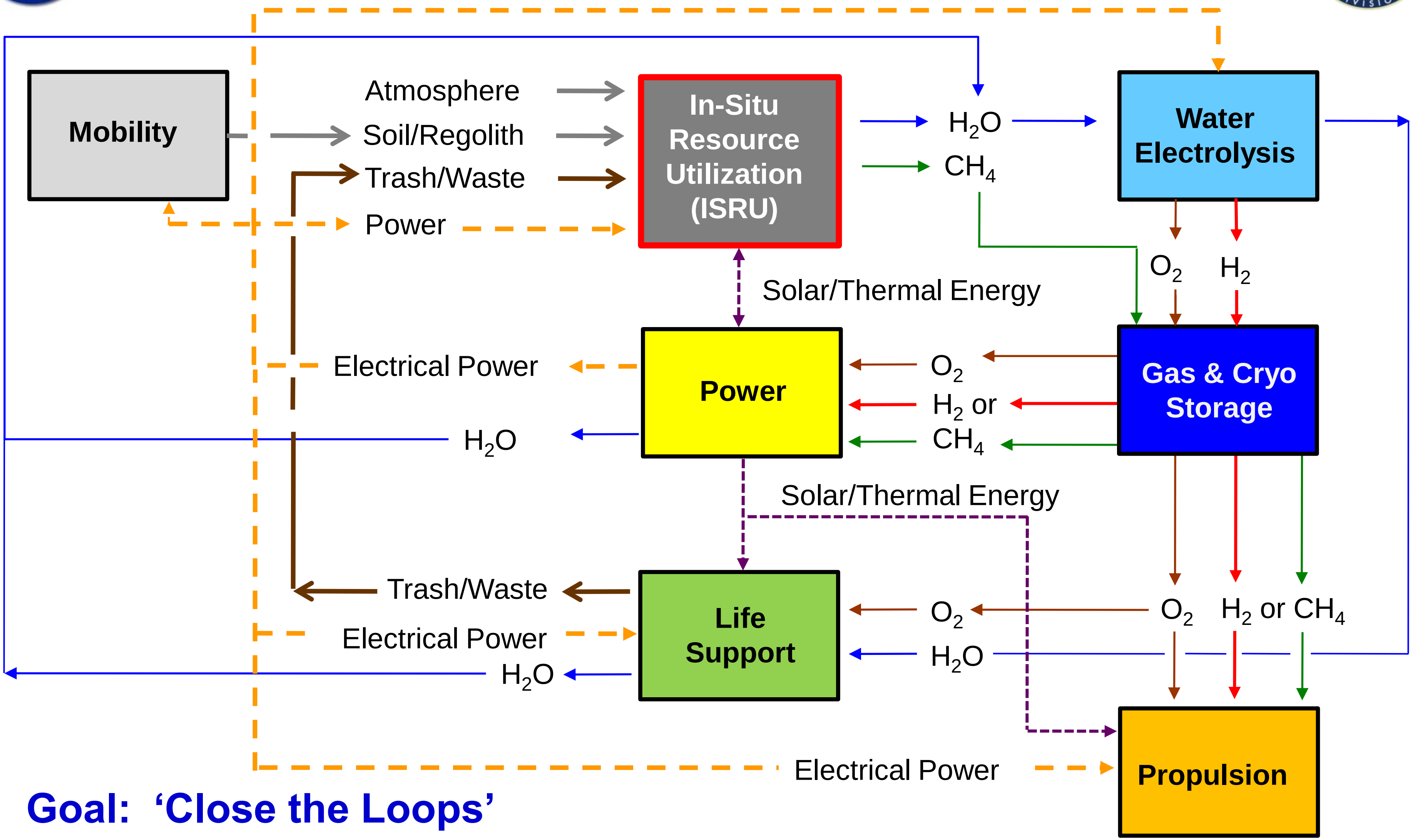
- Increases Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.

Enables Space Commercialization

- Provides infrastructure, technologies, and market to support space commercialization
- Propellants, energy, metals, and manufacturing feedstock



Integrated Power & Consumable Cycles for ISRU – Power – Propulsion – Life Support



Goal: 'Close the Loops'

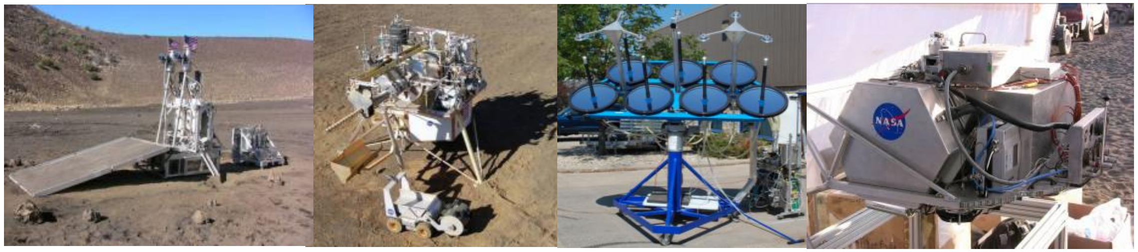
- Common fluids, pressures, quality, and standards
- Common storage, distribution, and interfaces
- Common technologies and hardware for flexibility and reduced DDT&E

NASA ISRU Development Areas

Excavation for O_2 Extraction

Site Preparation-Area Clearing

O_2 Production/Volatile Extraction from Soils

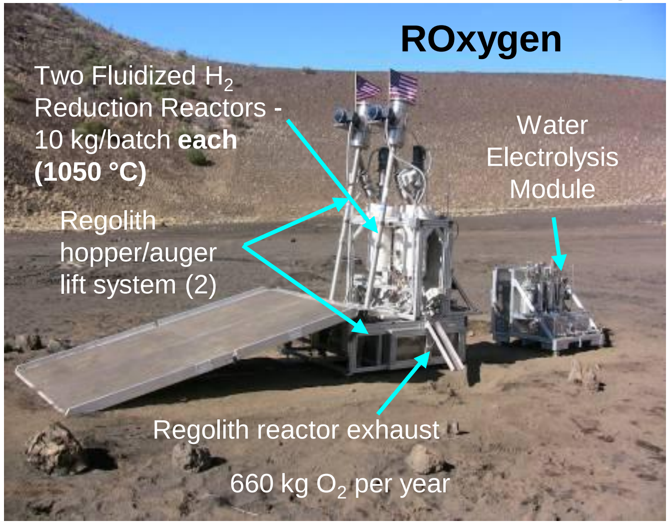


Resource Prospecting/Mapping

Surface Sintering/Hardening

Lunar Processing – Oxygen & Metal Extraction

Hydrogen Reduction of Regolith



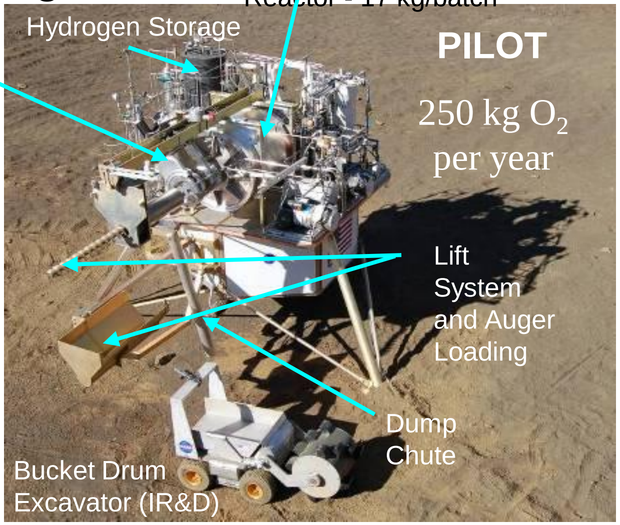
1. Heat Regolith to >900 C

2. React with Hydrogen to Make Water

3. Crack Water to Make O_2

O_2 Cryo Tank

Rotating H_2 Reduction Reactor - 17 kg/batch



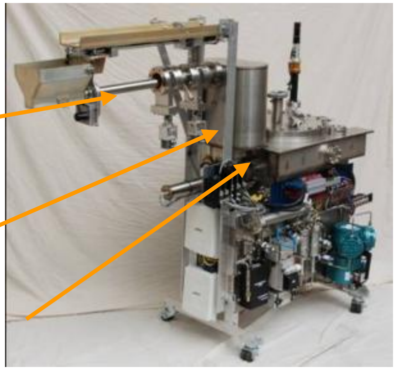
$$FeO + H_2 \rightarrow Fe + H_2O; \qquad 2H_2O \rightarrow 2H_2 + O_2$$

Carbothermal Reduction of Regolith

Lift System and Auger Loading

Regolith Storage – 1 day

Regolith Reduction Chamber



1. Melt Regolith to >1600 C

2. React with Methane to CO

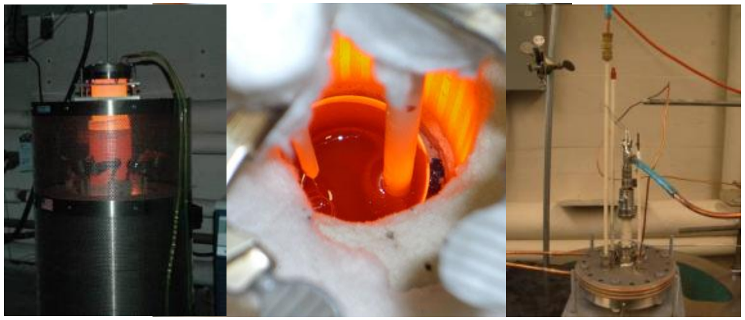
3. Convert CO to Methane & Water

4. Crack Water to Make O_2

$$SiO_4 + CH_4 \rightarrow CO + 2H_2 + Si; \quad \text{- - - -}> \quad CO + 3H_2 \rightarrow CH_4 + H_2O;$$
$$2H_2O \rightarrow 2H_2 + O_2$$

NASA/JSC/EP/JAG

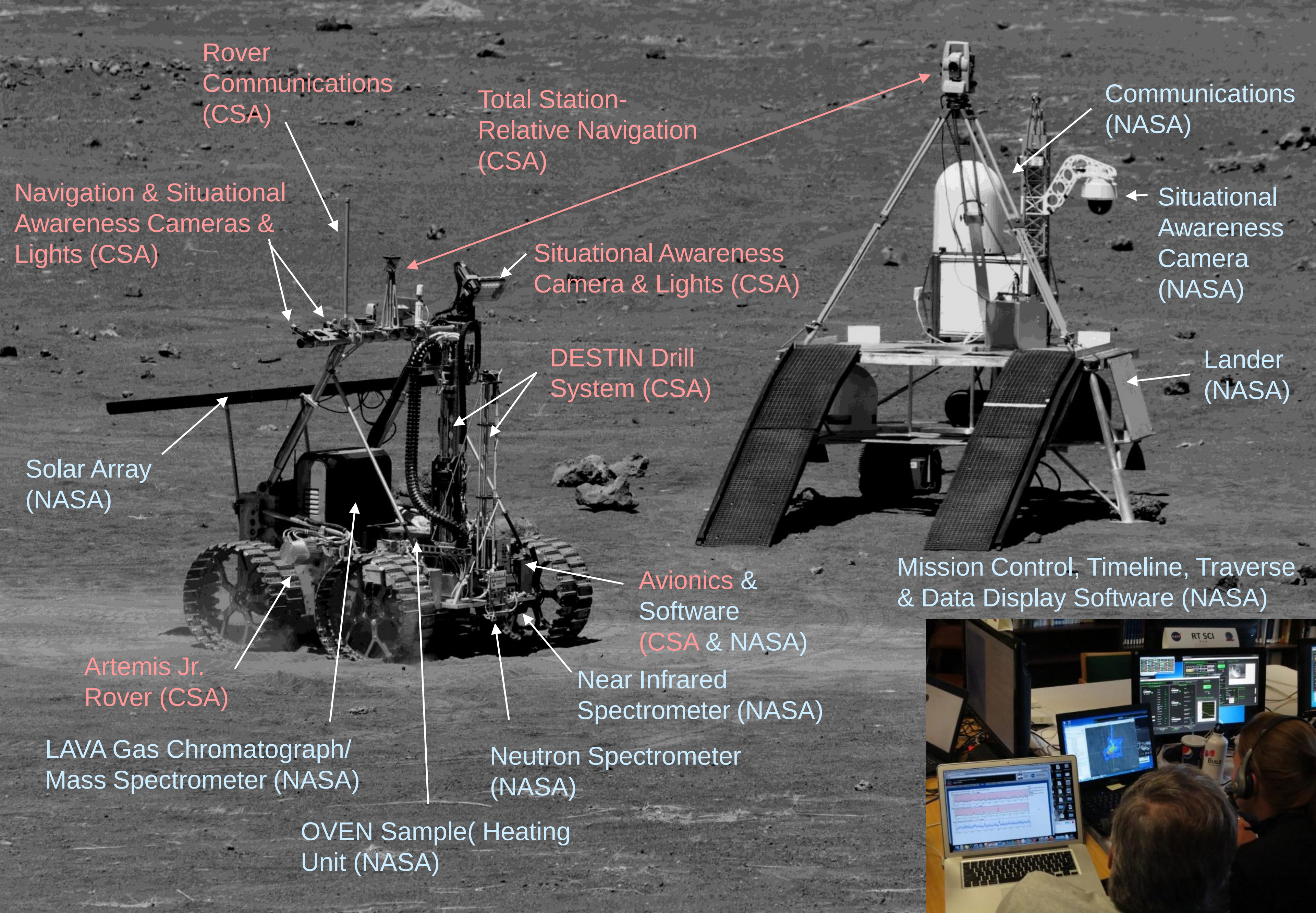
Molten Electrolysis of Regolith



1. Melt Regolith to >1600 C

2. Apply Voltage to Electrodes To Release Oxygen

Proposed “RESOLVE” Lunar Polar Ice/Volatile Prospecting Mission



Mars Resources, Processes & Products

MARS RESOURCES

ATMOSPHERE

Carbon Dioxide (CO_2)	95.5%
Nitrogen (N_2)	2.7 %
Argon (Ar)	1.6%
Oxygen (O_2)	0.15%
Water (H_2O)	<0.03%

SOIL

$Fe_2Mg_2S_{i2}O_8$
Fe_2O_3
$FeSiO_3$

SURFACE VOLATILES

Polar Water (H_2O)	TBD
Perma Frost (H_20)	TBD
Frozen CO_2	TBD

Thermal Volatile Extraction

Zirconia Solid Oxide CO2 Electrolysis (ZE)

$2CO_2 \xrightarrow{900 - 1000\ C} 2CO + O_2$ [Pt catalyst] → O_2

Sabatier Catalytic Reactor (SR)

$CO_2 + 4\,H_2 \overset{200 - 300\ C}{\rightleftharpoons} CH_4 + 2H_2O$ [Ru catalyst] → H_2O, CH_4

Reverse Water Gas Shift (RWGS)

$CO_2 + H_2 \overset{400 - 650\ C}{\rightleftharpoons} CO + H_2O$ → H_2O

Complex Hydrocarbon Manufacturing

$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$ [Photosynthesis] → O_2, Sugar

$2CO_2 + 6H_2 \rightarrow 4H_2O + H_2C{=}CH_2$ → H_2O, Ethylene

$CO + 2H_2 \rightarrow CH_3OH$ [ZnO catalyst] → Methanol

Methane Reformer

$CO + 3H_2 \xrightarrow{250\ C} CH_4 + H_2O$ [Ni catalyst] → H_2O, CH_4

Water Electrolysis (WE)

$2H_2O \xrightarrow{25\ C} 2H_2 + O_2$ → O_2, $2H_2$

Hydrothermal Reduction

$Fe_2Mg_2Si_2O_8 + 2H_2 \xrightarrow{1000\ C} Mg_2SiO_4 + SiO_2 + 2H_2O + 2Fe$ → $2H_2O$, 2Fe

$Fe_2O_3 + 3H_2 \xrightarrow{1000\ C} 3H_2O + 2Fe$ → $3H_2O$, 2Fe

$2FeSiO_3 + 2H_2 \xrightarrow{1000\ C} 2SiO_2 + 2H_2O + 2Fe$ → $2H_2O$, 2Fe

Carbothermal Reduction

$Fe_2Mg_2Si_2O_8 + 6CH_4 \rightarrow 2MgO + 6CO + 12H_2 + 2Fe + 2Si$ → $12H_2$, 2Fe, 2Si

$Fe_2O_3 + 3CO \rightarrow 3CO_2 + 2Fe$ → 2Fe

$2FeSiO_3 + 2CH_4 \rightarrow 2CO + 4H_2O + 2Fe + 2Si$ → $4H_2O$, 2Fe, 2Si

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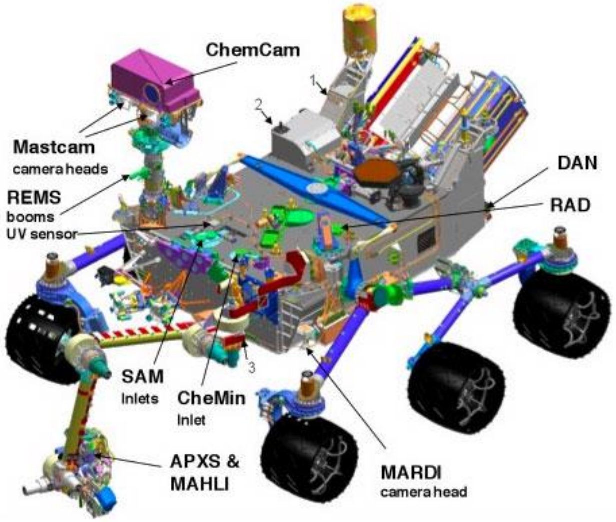
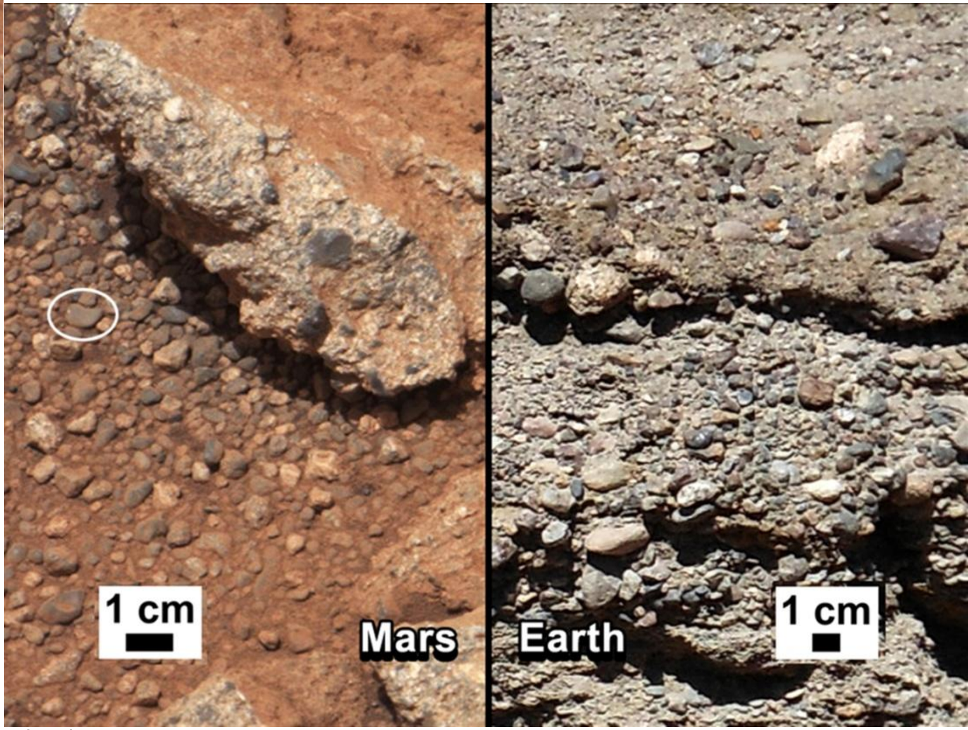
SUB-SURFACE VOLATILES

Mars MSL Rover "Curiosity"

Sedimentary Conglomerate?

- **Fractured outcrop w/ clean exposed surface**
- **Rounded gravel clasts few cm's in size**
- **White matrix material**
- **Gravel sized rocks have eroded off**





Summary

Planetary Drilling **is a key technology for future space exploration**

- **Science: geology, climate history, astrobiology**
- **Resource prospecting**
- **Unique requirements drive unique design solutions**

Planetary Resources **enable robust human space exploration**

- **In-situ production of oxygen, water, propellants, shielding, etc.**
- **“7.5-to-1” gear ratio for the Moon**
- **Moon:**
  - **Regolith → Oxygen**
  - **Polar shadowed craters → Water ice**
- **Mars:**
  - **Carbon dioxide atmosphere → Oxygen**
  - **Poles → Water ice**
  - **Aquifers?**